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THERMAL RESPONSES TO HIGH-FREQUENCY ELECTROMAGNETIC RADIATION F--ETC(U)
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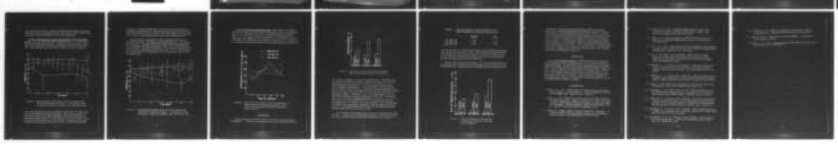

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THERMAL RESPONSES TO HIGH-FREQUENCY ELECTROMAGNETIC RADIATION FIELDS

September 1976

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USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
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NOTICES

This interim report was submitted by personnel of the Radiation Physics Branch, Radiobiology Division, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas, under job order 7757-01-45.

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The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act of 1970 and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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THERMAL RESPONSES TO HIGH-FREQUENCY ELECTROMAGNETIC RADIATION FIELDS

INTRODUCTION

It has been stated, especially since the recent publication of Michaelson (15), that heat generation is the predominant effect of electromagnetic radiation (EMR) fields on mammalian systems. Anne et al. (2) made quantitative predictions on the distribution of such heat; Guy et al. (6) developed a quasi-static model; and later, Durney et al. (4) made quantitative predictions of thermal deposition in both man models and experimental animals.

Massoudi et al. (12) and Allen et al. (1) report power absorption comparisons of theory and experiment well within the combined errors of estimates of the procedures used in 10-50-MHz EMR fields. MacDougal et al. (11) report the distribution of this energy as determined by thermography in a variety of models and field impedances. Gandhi (5) has shown the resonance frequency for man to be in the vicinity of 40-50 MHz and for smaller animals at much higher frequencies. Scale factors presented by Johnson et al. (9) show that power absorption in man is 2-3 times that of a monkey at 20 MHz, with proportionately larger scaling factors for smaller animals.

While these "scaling factors" apply to the amount of power deposited, the thermal results of such scaling are by no means certain. One aspect of uncertainty, demonstrated by Guy et al. (7), is the nonuniformity of thermal distributions; e.g., particularly intense heating in the lower limbs during exposure of human phantoms to predominately electric fields (7). Thermographs obtained by MacDougal et al. (11) have substantiated these findings.

The nonuniformity of power distribution is a vexing problem, and has at least two other problems superimposed: (1) the involvement of circulation in promoting thermal diffusion, and (2) the basal heat-production and heat-exchange capability of the organism. Such a relationship was implicit in the proposal by Mumford (16) for exposure of man to EMR fields. Krogh (10) and Dubois (3) showed that the basal metabolic rate, hence heat production, is roughly related to the body surface area (a). Surface area is in turn related to a fractional power of the body weight (W). Heat production (H_T) can thus be related to body weight as

$$H_T = a W^k$$

Massoudi et al. (13) have shown that power absorption at frequencies below resonance is proportional to the height, width, and length in the propagating wave. Thus, specific power absorption rate (S) is a function of height, width, length, conductivity, and real and imaginary dielectric constants, so

$$H_T = S + a W^k.$$

The effort being reported here was carried out to determine some of the thermal consequences of exposure to 26-MHz EMR fields and to determine field levels at which these thermal changes were minimized in conscious primates. Previous experience with anesthetized primates exposed to 1320-mW/cm^2 fields at 26 MHz has demonstrated core temperature increases (17).

METHODS AND MATERIALS

Twelve male rhesus monkeys weighing 3.58 ± 0.44 kg were used. They were housed in the vivarium, fed a commercial ration twice daily, and allowed water ad libitum. When RF exposures were made, both control and experimental animals were transported by truck to the RF radiation facility. Although occurring during the early summer and very early in the morning, this transport (10 min) still exposed animals to a slightly higher temperature than that maintained in either the vivarium or the RF facility. All animals were placed in slatted cages in the vivarium prior to transport, and were retained in these cages until return to the vivarium at the completion of the day's exposure.

Each day during a 5-day work week, 2 animals were exposed to 26 MHz radiation for 6 hours in a rectangular coaxial HF-band transmission line, while the remaining 10 animals were placed adjacent to, but outside of, the exposure volume. On each successive day, 2 other animals were exposed to the field; thus 10 animals were exposed over a 5-day week, so the 12 monkeys were never exposed to RF fields on the same day of the week. Exposure at each succeeding power level was begun with the next two monkeys in order, so that new power levels were never begun with the same monkeys. Animals were denied access to food and water about 8 hours, from the time they left the vivarium until the termination of the exposure period; afterwards they were given apples.

Rectal temperatures were recorded using thermistor probes (Yellow Springs Instrument Telethermometer Model 73). Temperatures were estimated $\pm 0.1^{o}$ C. The thermistor was calibrated with an NBS-certified mercury thermometer (Taylor Instrument Co.). (See Table 1 for calibration comparisons.)

TABLE 1. CALIBRATION OF YELLOW SPRINGS INSTRUMENT THERMISTOR WITH NATIONAL BUREAU OF STANDARDS MERCURY THERMOMETER (^{o}C)

Thermistor reading	Thermometer reading
35.6	35.3
35.4	35.3
34.9	35.1
35.2	34.8

Skin temperatures were measured using infrared emission recorded by a radiometer equipped with a copper-doped germanium detector (Barnes Instrument Co., model R8T-1). This instrument has a focal spot of approximately 4 mm^2 achieved through the use of an 8-inch cassegrainian reflecting telescope. Calibrations were performed by immersing a blackened copper strip in water contained in a Dewar flask. The spot used for calibration was carefully shielded from water vapor and any stray air currents. Water temperature was measured with the same NBS-certified thermometer used to calibrate the thermistor probes (Table 2, calibration data). Replicate temperature estimations from the same spot agreed to less than 0.01^{o} C. The radiometer was used as a null indicator, thus avoiding difficulties with amplifier nonlinearities.

The temperature and humidity of the exposure volume and the air around the control animals were continuously monitored with a calibrated recording thermometer/hygrometer. Thus, all the temperatures reported in this paper are referred to a single precision laboratory thermometer. Ambient temperature was maintained at $22.2^{o} \pm 1.1^{o}$ C.

Skin temperatures were recorded using infrared emissivity, from infraorbital skin folds just superior to the zygomatic arch. This particular area has the advantages of little or no thermal shielding from hair or other obstruction and being easily located by visible landmarks. Because of the lack of hair, the skin temperatures recorded are probably lower than those of the rest of the body.

TABLE 2. CALIBRATION OF BARNES RADIOMETER WITH NATIONAL BUREAU OF STANDARDS MERCURY THERMOMETER (°C)

	Radiometer reading	Thermometer reading
Black body	25.99	25.1
	26.06	25.1
Water-filled beaker	36.42	35.3
	35.16	35.1
	34.67	34.8

Power was applied to the HF-band coaxial transmission line from an FRT-6B transmitter operating as a continuous-wave generator at 26 MHz $\pm$ 0.1 MHz. Transmitter power was continuously monitored with Bird power meters and directional couplers, while frequency was monitored with a Systron-Donner frequency counter.

The electric (E) and magnetic (H) fields were measured with E- and H-field probes calibrated at the National Bureau of Standards. Dipole measurements made over the exposure volume for each cage indicate 3% maximum variation in the E-field. Comparison of average E-fields shows that the cage in the position nearer the load end is 3% higher than the cage near the feed end. Loop antenna measurements also indicated the H-field to be constant and within 3% over each exposure volume, with the cage near the feed end being 10% higher than the cage at the load end. Incident power density was calculated by multiplying average E by average H. It was determined that the average incident power density of 1000 mW/cm^2 was achieved with 34 kW feed, 750 mW/cm^2 with 25 kW feed, and 500 mW/cm^2 with 16.5 kW feed; thus, these values of incident power were held constant within $\pm$10% for the duration of the exposures. The ratio E/H for these experiments was determined to be 450 ohms $\pm$40 ohms.

The exposed animals were placed under each of two recording monopoles. The small image field developed by the animal perturbed the field around the monopole, and each position change made by the experimental animal was recorded as a field perturbation in the monopole recording. Counting the number of such perturbations during successive 10-minute periods gave a rough indication of the animal's activity (Fig. 1).

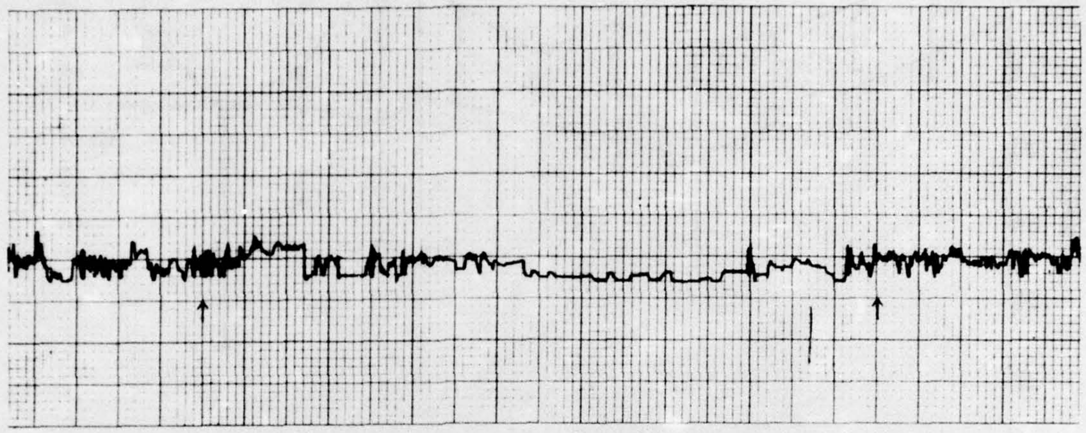

Figure 1. "Activity" perturbations of monkeys placed directly under recording monopoles. The small image fields developed by the animals perturbed the field around the monopoles, and the perturbations in a 10-min period (between the small arrows) were counted and used as a rough indicator of "activity."

RESULTS

Figures 2 through 4 display the skin and rectal temperatures of primates exposed to 1000-, 750-, and 500-mW/cm^2 fields at 26 MHz, together with the temperatures of their companion controls. Each experimental and control point is the mean of 10-50 individual measurements on 10 experimental animals.

<u>1000-mW/cm^2 Fields (Fig. 2)</u>. One-half hour after field application, rectal temperature rose from 38.1° to 39.4° C, and skin temperature from 36.1° to 38.6° C. These initial increases were followed by a fall during the next hour to 38.8° C rectal and 37.2° C skin temperature. Rectal temperature remained stable from this point until the end of the experiment. Control rectal temperature fell slightly and control skin temperature fell about 2° C during this period. After 3.5 hours, the skin temperature of the irradiates increased until the end of the fifth hour when it began to decline; the final reading was about 0.1° C above baseline.

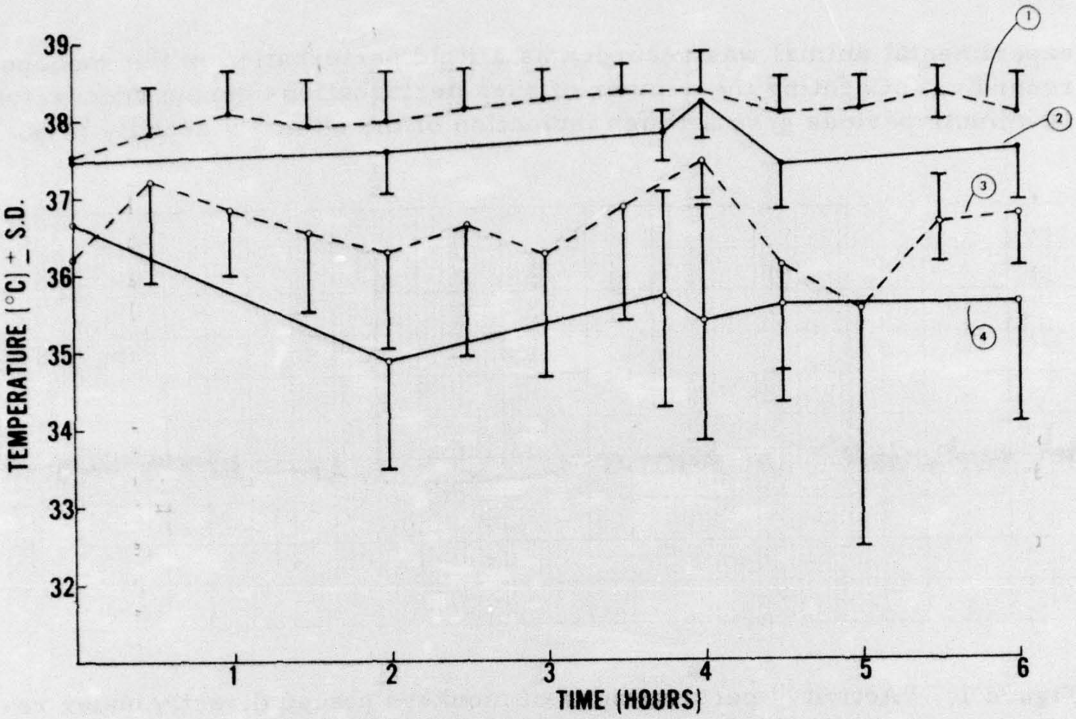

Figure 2. Temperature changes in control and irradiated monkeys during 6 hours exposure to HF-band EMR fields at 26 MHz, 1000 mW/cm^2: (1) irradiate, rectal; (2) control, rectal; (3) irradiate, skin; (4) control, skin.

750-mW/cm^2 Fields (Fig. 3). The skin temperature increased 1.4° C during the first half hour, then immediately declined 1.5° C during the next 1.5 hours. At the end of the sixth hour, the skin temperature was at approximately baseline. The rectal temperature increased 0.4° C during the first hour, reaching an apparent equilibrium at about 37.8° C.

500-mW/cm^2 Fields (Fig. 4). As in the higher fields, the skin temperature rose in the first half hour and then declined. The rate of rise, however, during the first half hour (2° C/hr) was less than that seen at 750 and 1000 mW/cm^2 (2.8° and 2.6° C/hr). The skin temperature rose during the fourth hour, then declined. At the end of the experiment, the skin temperature was 0.5° C above baseline. The rectal temperature reached an apparent equilibrium of about 0.6° C above baseline. In each set of experiments the control skin temperatures

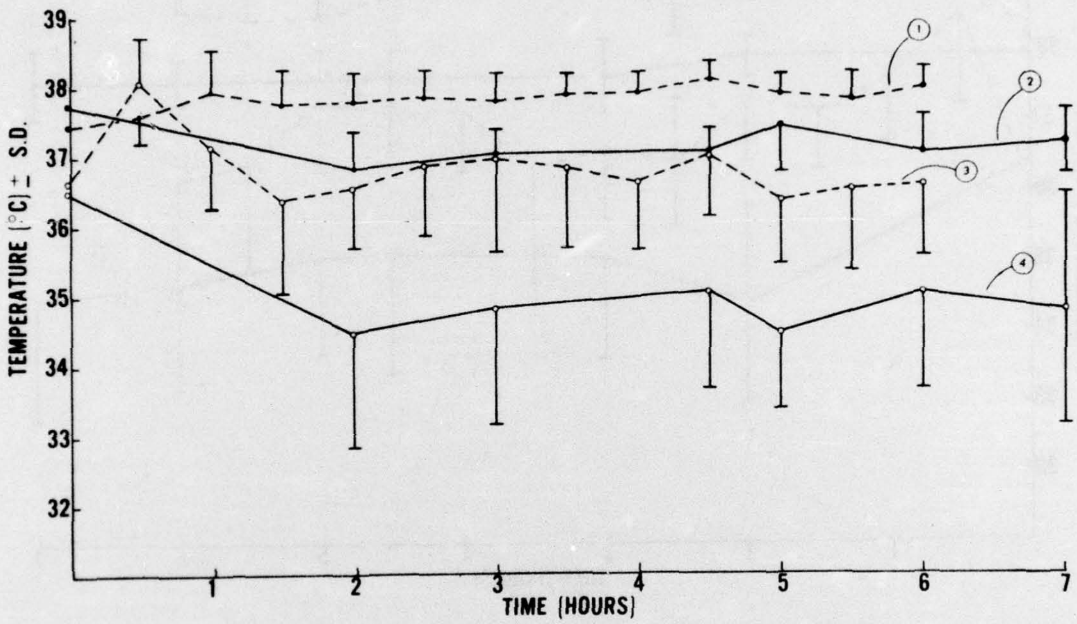

Figure 3. Temperature changes in control and irradiated monkeys during 6 hours exposure to HF-band EMR fields at 26 MHz, 750 mW/cm^2: (1) irradiate, rectal; (2) control, rectal; (3) irradiate, skin; (4) control, skin.

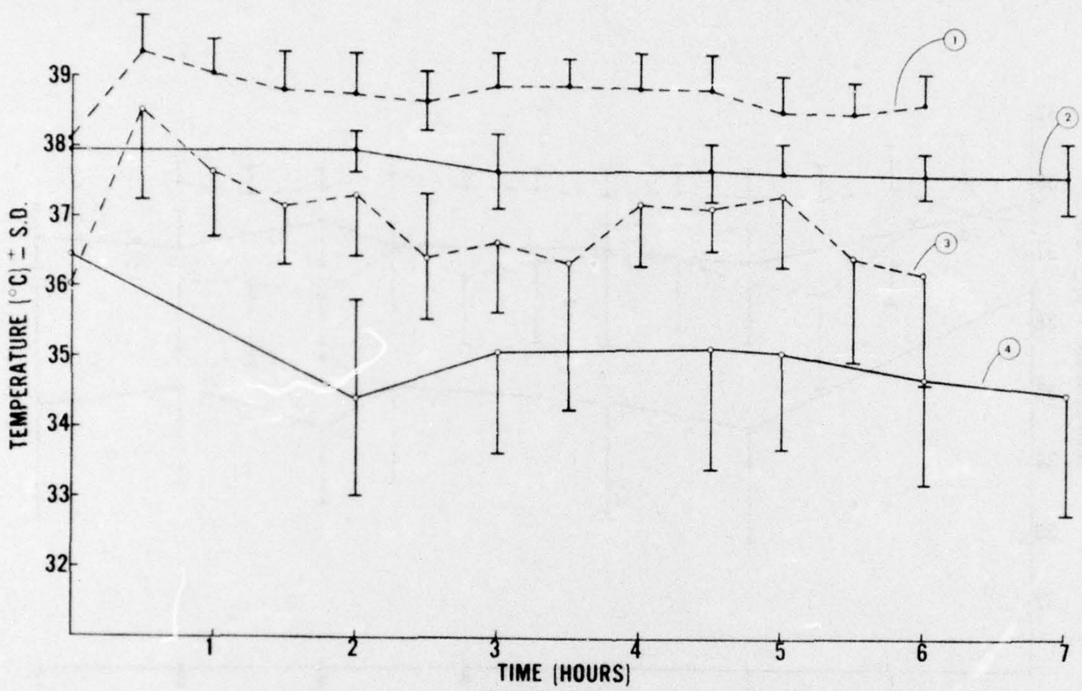

Figure 4. Temperature changes in control and irradiated monkeys during 6 hours exposure to HF-band EMR fields at 26 MHz, 500 mW/cm^2: (1) irradiate, rectal; (2) control, rectal; (3) irradiate, skin; (4) control, skin.

fell over the first 2 hours, then rose and fluctuated slightly during the remainder of the experimental period. The control rectal temperatures remained relatively constant over the entire experiment.

Uninterrupted Exposure to 500- and 750-mW/cm^2 Fields (Figs. 5 and 6). Because obtaining rectal temperatures every 30 minutes required interrupting the exposure, continuous 6-hour runs were made with rectal temperatures obtained immediately before and after radiation. The results for the 500-mW/cm^2 field are shown in Figure 5.

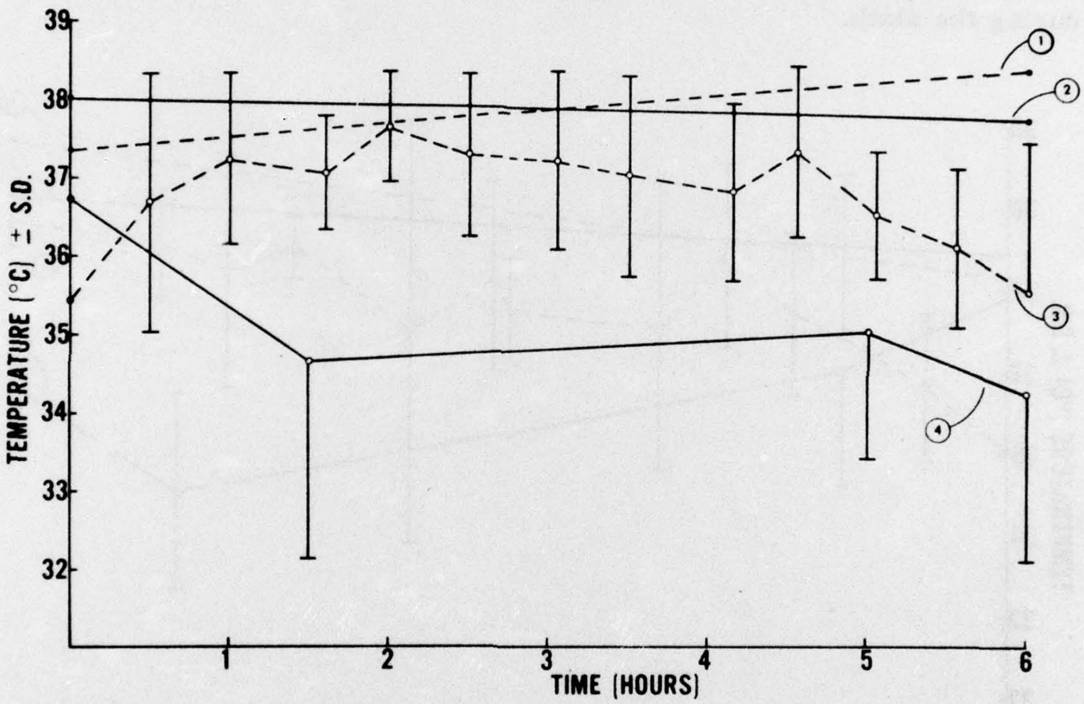

Figure 5. Initial and final temperatures of primates exposed to 500-mW/cm^2 fields for 6 hours: (1) irradiate, rectal; (2) control, rectal; (3) irradiate, skin; (4) control, skin.

The rectal temperature of the irradiated animals was 1° C higher after 6 hours of exposure than at the beginning. The skin temperature (as determined remotely with the radiometer while the field was being applied) increased nearly 2° C during the first 2 hours of exposure and remained elevated until the 4.5-hour period, then began to cool, and reached its initial value by the end of 6 hours. As in the interrupted exposures, the rectal temperature of the control animals remained constant throughout the run. The skin temperature of the control monkeys declined for the first 1.5 hours, then rose slightly and remained more or less constant throughout the rest of the exposure period.

Figure 6 shows the data for a 6-hour continuous exposure to 750-mW/cm^2 fields. The final rectal temperature was 1.7^{o} C higher than the initial. The skin temperature tended upward throughout the run, eventually reaching a temperature about 2.8^{o} C higher than the initial reading. The rectal temperature of the controls was essentially the same at the beginning and at the end of the run; their skin temperature declined about 1.4^{o} C during the first 5 hours, then rose 1.3^{o} C during the sixth.

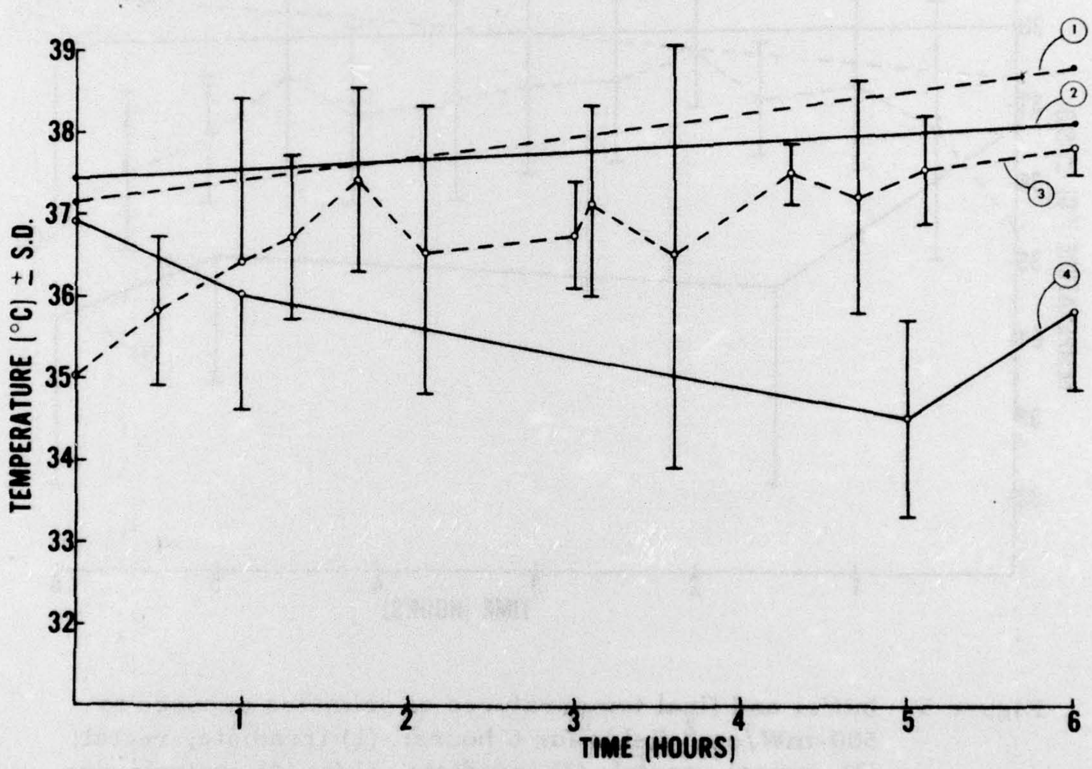

Figure 6. Initial and final temperatures of primates exposed to 750-mW/cm^2 fields for 6 hours: (1) irradiate, rectal; (2) control, rectal; (3) irradiate, skin; (4) control, skin.

Activity During the Radiation Periods. Net activity, as obtained from perturbation of fields around the monopoles, for all the radiation periods was tabulated for successive 10-minute periods (plotted in Fig. 7). At all power levels, an increase in activity appears to be associated with changes in skin temperature; i.e., the peak in activity in the 500-mW/cm^2 group, seen between 3.5 and 4 hours, occurred at a time when the skin temperature was increasing fairly sharply (Fig. 4).

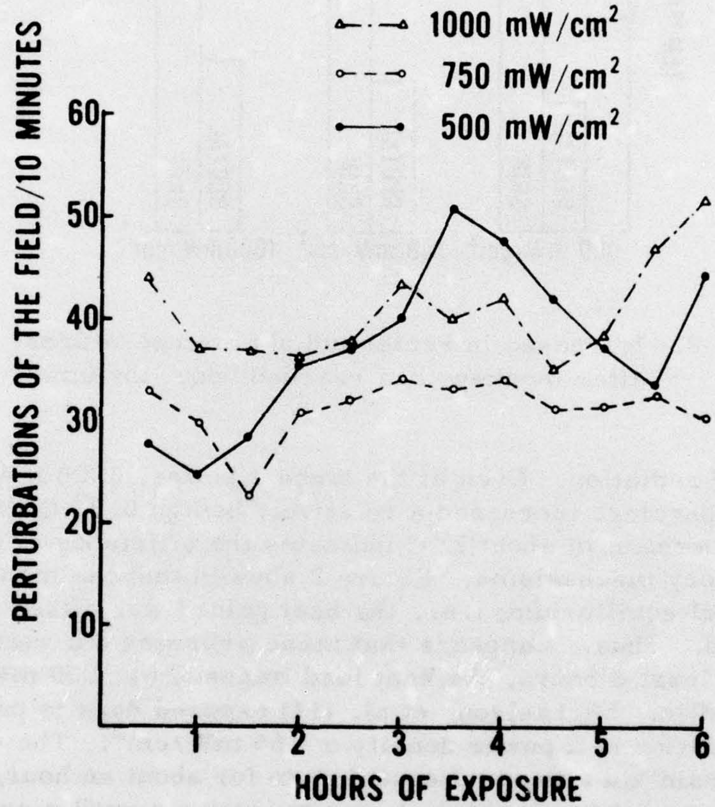

Figure 7. Net "activity" as obtained from perturbations of fields around the recording monopoles. Each point is the mean of the field perturbations in a 10-min period.

DISCUSSION

Figure 8 shows the increase in skin and rectal temperatures after "equilibrium." These are temperatures averaged over the period from

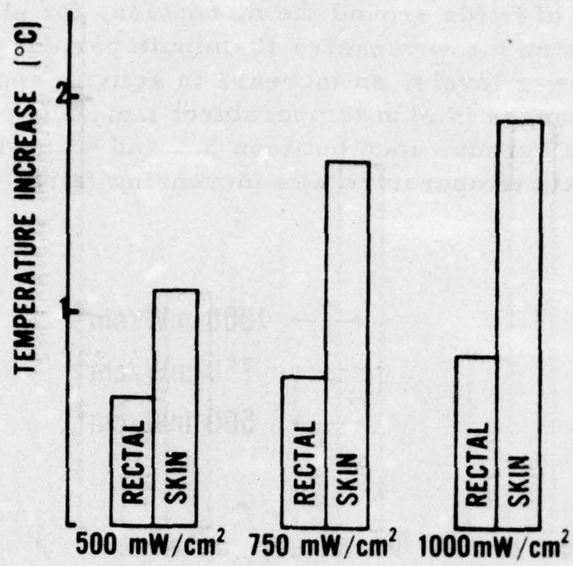

Figure 8. Increases in rectal and skin temperatures after monkeys had reached "equilibrium."

2 to 6 hours of radiation. Even at the highest power, 1000 mW/cm^2, the rectal temperature increased a relatively benign 0.8^o C; the skin temperature increase of about 2^o C indicates the efficiency of the thermoregulatory mechanisms. Figure 2 showed that the monkeys were in thermal equilibrium; i.e., the heat gained was offset by the heat dissipated. Thus, it appears that these primates can rather easily handle, for at least 6 hours, the heat load imposed by 1000 mW/cm^2 applied at 26 MHz. Michaelson et al. (14) exposed dogs to pulsed 2800-MHz radiation at a power density of 165 mW/cm^2. The animals were able to maintain a thermal equilibrium for about an hour, at which time the rectal temperature began to increase until a critical temperature of 1.7^o C above control was reached. If the exposure was not stopped, the temperature continued to rise and collapse and death occurred. At a power density of 100 mW/cm^2, the dogs remained in thermal equilibrium over a 6-hour period.

Cooling rates of the monkeys after cessation of radiation are shown in Table 3. Rectal and skin temperatures taken 10 minutes after radiation were subtracted from those taken immediately after radiation.

TABLE 3. COOLING RATE (° C/HR) OF RECTAL AND SKIN TEMPERATURES AFTER RADIATION

	Rectal	Skin
500 mW/cm^2	0.36	1.74
750 mW/cm^2	2.64	2.46
1000 mW/cm^2	3.54	1.75

Such cooling rates are sufficient to bring the core and skin temperature to normal values in an hour or less. This indicates that thermoregulatory mechanisms have not been impaired by 6 hours of radiation even at 1000 mW/cm^2, and that the monkeys were able to easily dissipate the heat load following cessation of radiation.

Figure 9 shows the rates of change, in $^{\circ}$C/hr, during the first half hour of exposure. The large rate of rectal temperature increase seen at 1000 mW/cm^2 is reflected in a much higher rate of increase for skin

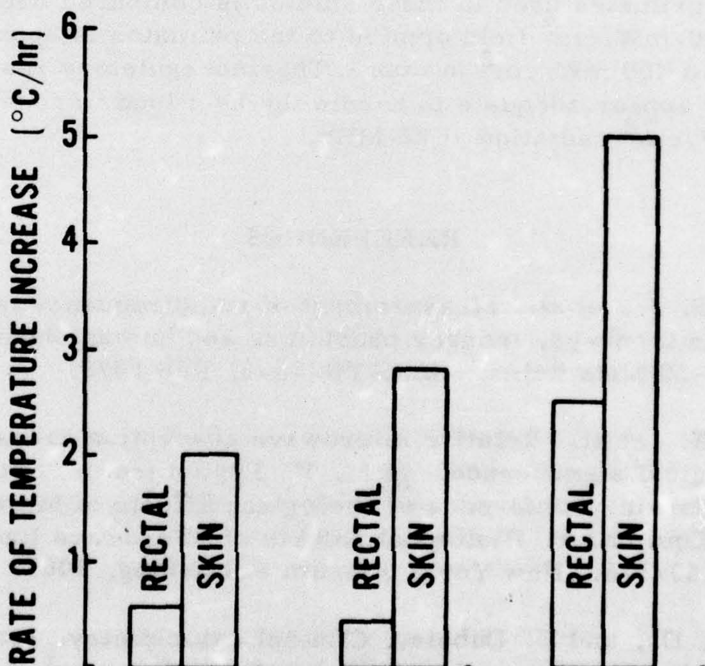

Figure 9. Rates of change in rectal and skin temperatures during the first half hour of exposure.

temperature, indicating an increased blood perfusion of the skin. Signals from external temperature perturbations, sensed by the thermoreceptors located throughout the body, can be relayed to central thermoregulatory centers before the disturbance has reached the body core. The thermoreceptors are sensitive to the rate of temperature change, and are a "feed forward" system to provide advance warning of an impending core temperature increase so that appropriate physiologic responses can be made (8). Thus, the increase in blood perfusion in the skin results in an increase in eccrine secretion, with consequent evaporative cooling, and is reflected in the decrease in skin temperature after the first half hour (Fig. 2).

CONCLUSION

In primates (Macaca mulatta), 6 hours of 26-MHz radiation produced a mild hyperthermia characterized by an increase in skin and core temperature. An immediate rise in skin temperature with subsequent skin cooling indicated an activation of thermoregulatory mechanisms such as cutaneous vasodilation and sweat production. When the size of the primates used in these studies is compared with a 1.8-m man, a 1000-mW/cm^2 field applied to the primates is approximately equivalent to 400 mW/cm^2 in man. Thermoregulatory responses in the monkey appear adequate to handle the heat load imposed by 6 hours of 1000-mW/cm^2 radiation at 26 MHz.

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